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Automatically Discovering Hidden Transformation Chaining Constraints

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Abstract. Model transformations operate on models conforming to precisely defined metamodels. Consequently, it often seems relatively easy to chain them: the output of a transformation may be given as input to a second one if metamodels match. However, this simple rule has some obvious limitations. For instance, a transformation may only use a subset of a metamodel. Therefore, chaining transformations appropriately requires more information.

We present here an approach that automatically discovers more detailed information about actual chaining constraints by statically analyzing transformations. The objective is to provide developers who decide to chain transformations with more data on which to base their choices. This approach has been successfully applied to the case of a library of endogenous transformations. They all have the same source and target metamodel but have some hidden chaining constraints. In such a case, the simple metamodel matching rule given above does not provide any useful information.

1 Introduction

One of the main objectives of Model-Driven Engineering (MDE) is to automatize software engineering tasks such as: the production of code from abstract models in forward engineering scenarios, the production of abstract models from code in reverse engineering scenarios, or a combination of the two previous cases in modernization scenarios. To achieve this automation, MDE relies on precisely defined models that can be processed by a computer. Each model conforms to a metamodel that defines concepts as well as relations between them. For instance, a Java metamodel has the concept of Java class, with the corresponding single-valued superclass relation (i.e., a class can only extend one other class). Similarly, the UML metamodel defines the concept of a UML class, with a multi-valued generalization relation (i.e., a class may extend several other classes). Many software engineering tasks such as those mentioned above can be performed by model transformations.

In order to reduce the effort of writing these transformations, complex tasks are generally not performed by complex transformations but rather by chains of simpler transformations. A model transformation chain is formed by feeding

the output of a first transformation as input to second one. Complex chains can consist of a large number of transformations. For instance, in order to analyze a Java model with a Petri net tool, a first transformation may operate from Java to UML, and a second one from UML to Petri net.

Model transformations are reusable. In our previous example, if a different target formalism is to be used, the Java to UML transformation may be reused, while the second one is replaced. Some model transformation libraries such as [1] are already available to leverage this possibility. Typically, each entry specifies the name of the transformation as well as its source and target metamodels. Some documentation may also be available. A model-driven engineer confronted to a model transformation problem may first lookup for existing transformations. If no pre-existing transformation exactly performs the required task, some pieces may be used to form a chain into which only simpler new transformations need to be inserted. Source and target metamodel information may be used to chain transformations. A transformation from B to C may for instance be attached at the output of a transformation from A to B.

However, chaining transformations properly is generally a more complex task in practice. Knowing the source and target metamodels of a transformation is not enough. For instance, a transformation may only target a subset of its declared target metamodel. Feeding its output to a second transformation that takes a different subset of the same metamodel as input will typically not yield correct results. Computing a class dependency graph from a Java model by reusing a transformation that takes UML Class diagrams as input may not be possible with the Java to UML transformation targeting Petri nets used in the previous example. While this new transformation requires the class structure to be retrieved from the Java model, the initial transformation may have been limited to the generation of the Activity diagrams required for the generation of Petri nets.

The case of endogenous transformations is even more problematic. Because these transformations have the same source and target metamodel, they can in theory be inserted in a chain anywhere this metamodel appears. A collection of such transformations operating on the same metamodel could also be chained in any order. In practice, this may not lead to correct results (e.g., because a transformation may remove an element from the model that is required for another transformation to perform correctly).

Chaining transformations actually requires more precise knowledge about the individual transformations. For instance, if transformation t_1 relies on some information that is dropped by transformation t_2 then t_1 cannot be applied after t_2 . This knowledge may be available in a documentation of some sort, but this is not always the case. One may also look at the insides of a transformation (i.e., its implementation), but this requires knowledge of the transformation language (there are several languages, and not everybody is an expert in all of them).

The situation would be simplified if each transformation clearly identified the subset of a metamodel it considers. But this is not always enough. For instance, some endogenous transformations have a fixed point execution semantics (i.e.,

they need to be executed again and again until the resulting model is not changed any more). In such a case, the metamodel subset generated by each iteration may be different (especially the last iteration when compared to the previous ones for transformations that remove elements one at a time).

The purpose of the work presented here is to automatically discover information about what model transformations actually do. The resulting data may be used to help the engineer decide how to chain transformations, and may complement what is in the documentation of the transformation if there is one. A Higher-Order Transformation [19] that takes as input the transformations to analyze produces a model containing the analysis results. This model may then be rendered to various surfaces using other transformations.

We have applied this approach to the case of a set of endogenous transformations that are used for the translation between constraint programming languages. All transformations take the same pivot metamodel as source and target metamodel and are written in ATL [12,11,9] (AtlanMod Transformation Language). However, different subsets of this metamodel are actually consumed and produced by each transformation. By statically analyzing these transformations we have been able to discover what they do, and infer chaining constraints from this knowledge.

The reminder of the paper is organized as follows. Section 2 presents a scenario involving a number of endogenous transformations operating on a single metamodel. Our transformation analysis approach is described in Section 3, and its application is presented in Section 4. The results are discussed in Section 5. Finally, Section 6 concludes.

2 Motivating Example

2.1 Interoperability of Constraint Programming Languages

In Constraint Programming (CP), one of the main goals is to define problems based on variables, domains and constraints such that a CP solver can compute their solutions [16]. In CP, various kinds of languages are used to state problems. For instance, the language of the ECLⁱPS^e solver [2] is based on logic and Prolog, whereas OPL [8] (Optimization Programming Language) is a solver-independent language based on high-level modeling constructs. Some solvers have only programming APIs like ILOG Solver [14] or Gecode [17]. More recently, the definition of high-level modeling languages is becoming a hot topic in CP [15]. Then, new modeling languages have been developed such as Zinc and MiniZinc [13], Essence [7] and s-COMMA [18]. In these three cases, the high-level modeling language is translated into existing CP solver languages by using a flat intermediary language to ease the translation process and to increase the reusability of most transformations and reformulation tasks. This process is mainly achieved by hand-written translators using parsers and lexers.

In a recent work [4], model engineering was used to carry out this process from s-COMMA models to some solver languages. Then, this approach has been

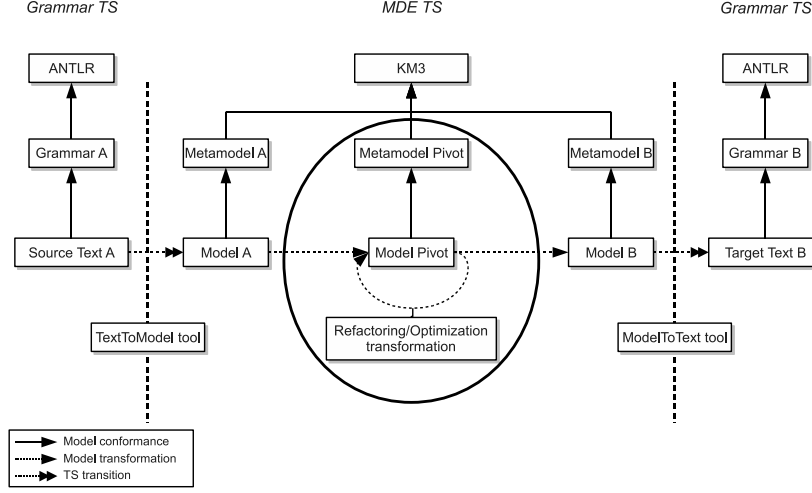


Fig. 1. A generic transformation process to translate CP models.

extended to get more freedom in the choice of the user modeling language [5] (see Figure 1). A flexible pivot CP metamodel was introduced, on which several transformations are performed to achieve generic and reusable reformulation or optimization steps. The transformation chain from a language A to a language B is composed of three main steps: from A to pivot, pivot refactoring and pivot to B. Steps on pivot models may remove some structural features not authorized by the target solver language. Thus, objects, if or loop statements may be removed and replaced by an equivalent available structure, i.e. objects are flattened, if are expressed as boolean expressions and loops are unrolled. All these refactoring steps are not mandatory when considering a CP modeling language and a CP solver language, since loop or if statements may be available in most CP solvers. Since no existing model engineering tool exists to automate the chaining of these model transformations according to a source and a target metamodel, the user must build chains by hand without any verification process.

The main part of the generic CP pivot metamodel introduced in [5] is shown on Figure 2. Indeed, CP models are composed of a set of constraints, variables and domains. They are classified in an inheritance hierarchy, with abstract concepts such as **Statement** that corresponds to all kinds of constraint declarations. High-level model constructs are defined according to existing modeling languages, such as the class and record concepts. Most of pivot models will only contained elements conforming only to a subset of the whole pivot metamodel.

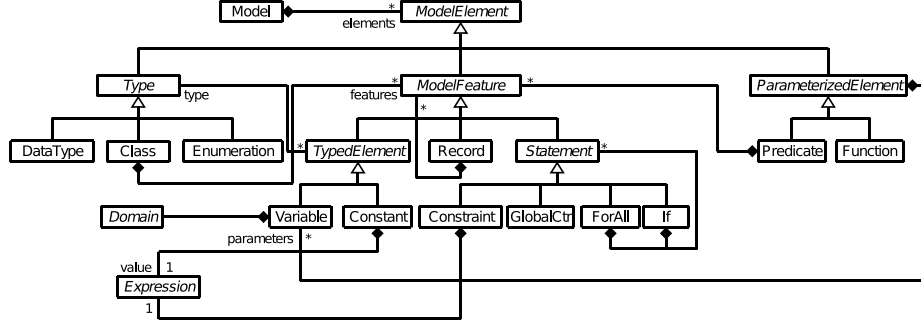


Fig. 2. Generic pivot metamodel for CP (excerpt).

2.2 Problem

In this paper, we want to tackle the issues relating to the efficient management of a set of endogenous transformations. Since the source and target metamodels are similar, no additional information can be extracted from the header of an ATL transformation. Considering only this knowledge, we may think that endogenous transformations can be chained without any problem, but this is not true. The solution proposed by [21] is therefore not sufficient to address this problem because it only considers the signature (or header) of transformations. As shown in the motivating example, endogenous transformations achieve model reformulation or optimization steps. They have to be efficiently and correctly chained to avoid useless steps — some steps may create elements that are removed by another step — and to reach the requirements of the target solver language. Our goal is to discover the role of endogenous model transformations in a parameterizable chain.

Endogenous transformations can be typed using their source and target element types, i.e. a sub-set of the metamodel of these models. Thus, considering the set of source elements of an endogenous transformation, we can assess the set of source models supported by it without any loss. The set of target elements also allows us to type generated models. Then, we may be able to verify endogenous transformation chains. Moreover, using a search/optimization algorithm we may be able to find the “best” chain and thus automating the chaining of endogenous transformations according to an input metamodel and to an output metamodel corresponding to a high-level exogenous transformation.

3 Transformation Analysis

3.1 Identifying Domains and Codomains

In order to correctly chain model transformations it is necessary to have a certain understanding of what they do. Although it is not enough, source and target

metamodels information is essential. The model M_B produced by a given transformation t_1 conforms to its target metamodel MM_B . It may only be fed as input to another transformation t_2 with the same metamodel MM_B as source metamodel.

This constraint may be expressed in functional terms as shown in [21]: transformations are considered as functions, and metamodels type their parameters in the case of simple transformations (Higher). For instance, if the source metamodel of t_1 is MM_A , and the target metamodel of t_2 is MM_C then: $t_1 : MM_A \rightarrow MM_B$ and $t_2 : MM_B \rightarrow MM_C$. In this notation the name of a metamodel is used to identify the set of models that conform to it. Thus, transformation t_1 is considered as a function of domain the set of models conforming to MM_A , and of codomain the set of models conforming to MM_B . In this example, if t_2 is total then it may be applied to the output of t_1 because the codomain of t_1 is also the domain of t_2 .

In practice, model transformations are often partial functions: they do not map every element of their declared domain to an element of their codomain. For instance, t_2 may only work for a subset $MM'_B \subset MM_B$. If t_1 is surjective (i.e., it can produce values over its whole codomain) then t_2 cannot be applied to all output models that t_1 can produce. This shows that problems can arise when the domain of transformations (i.e., their source metamodels) is underspecified (i.e., too broad). If codomains (or target metamodels) are also underspecified, then there may not be any actual problem. For instance, if t_1 only produces results over $MM''_B \subseteq MM'_B$ then t_2 may be chained to t_1 . Therefore, precisely identifying the actual domain and codomain of a transformation (i.e., definition domain and its image) would be an improvement over the current practice.

However, doing so is often complex because it requires deep analysis of transformations (e.g., not only source elements of transformation rules but also every navigation over source elements). Moreover, the semantics of a specific metamodel or transformation may make the problem harder. For instance, some endogenous transformations have a fixed point semantics and are called until a given type of element has been eliminated. Each intermediate step produces elements of this type except the last one. An example of such a transformation would eliminate for loops from a constraint program one nesting level at a time.

The objective of this paper is to provide a solution applicable with the current state of the art: actual domains and codomains cannot currently be 1) precisely computed, and 2) automatically checked. Therefore, if an approximation (because of 1)) is computed it must be represented in a simple form that the user may understand quickly (because of 2): the user has to interpret it). An example of such a simplification is the list of concepts (i.e., model element types coming from the metamodels) that are taken as input or produced as output of a transformation. This is the first analysis that has been applied to the motivating example presented in Section 2 with relatively poor results if considered alone.

3.2 Abstracting Rules

Other kinds of information may be used to better understand what a transformation does. ATL transformations are composed of rules that match source elements according to their type and some conditions (these form the source pattern of the rule), and that produce target elements of specific types (these form the target pattern of the rule). A transformation analyzer may produce an abstract representation of a set of transformation rules. This simplified description may take several forms.

One may think of representing the mapping between source and target meta-model concepts defined by the rules. Model weaving may be used for this purpose as shown in [6,11]. However, such a representation would be relatively verbose: there are as many mappings as rules, and the number of rules is typically close to the number of source or target concepts.

An additional simplification may be devised in the case of endogenous transformations in which elements are either copied (same target and source type) or mutated (different target and source types). These actions may be applied on every element of a given type, or only under certain conditions. Moreover, ATL lazy rules that are only applied if explicitly referenced (i.e., this is a kind of lazy evaluation) may also be used. Table 1 summarizes this classification of endogenous transformation rules. The first dimension (in columns) is the kind of action (copy or mutation) that is performed by the rule. The second dimension (in rows) corresponds to the cases in which the action is taken: always, under specific conditions, or lazily. Corresponding examples of rules taken from the motivating example are given below. No example of always or lazy mutation is given because there is no such case in the transformations of the motivating example.

Table 1. Classification of endogenous rules

	Copy	Mutation
Always		
Conditionally		
Lazily		

Listing 1.1 gives a rule that always copies data types. The target type (line 5) of such a rule is the same as its source type (line 3). It is concept *DataType* of the *CPPivot* metamodel in this listing. Moreover, it also copies all properties (e.g., source element name is copied to target element name at line 6). However, property-level information is not always so simple to identify. In many cases some properties are copied while others are recomputed. In order to keep the information presented to the user simple, property-level information is ignored in the current implementation of the transformation analyzer.

Listing 1.1. *Always copy* rule example

```
1 rule DataType {
2   from
3     s : CPPivot!DataType
4   to
5     t : CPPivot!DataType(
6       name <- s.name
7     )
8 }
```

A conditional copy happens when a copy rule has a filter or guard (i.e., a boolean expression that conditions the execution of the rule). The rule of Listing 1.2 is similar to the rule presented above in Listing 1.1 but has a guard specified at line 4. This rule performs a conditional copy.

Listing 1.2. *Conditionally copy* rule example

```
1 rule SetDomain {
2   from
3     s : CPPivot!SetDomain (
4       not s.parent.oclIsTypeOf(CPPivot!IndexVariable)
5     )
6   to
7     t : CPPivot!SetDomain (
8       values <- s.values
9     )
10 }
```

Listing 1.3 contains a lazy copy rule similar to the two previous rules of Listings 1.1 and 1.2 but starting with keyword *lazy* at line 1. Additionally, the rule presented here extends another rule via rule inheritance. This information is currently ignored during the abstraction process.

Listing 1.3. *Lazily copy* rule example

```
1 lazy rule lazyBoolVal extends lazyExpression {
2   from
3     b : CPPivot!BoolVal
4   to
5     t : CPPivot!BoolVal(
6       value <- b.value
7     )
8 }
```

An example of conditional mutation is given in Listing 1.4. This rule is a mutation because the target type *IntVal* (line 7) is different from the source type *VariableExpr* (line 3). It is conditional because there is a filter at line 4.

Listing 1.4. *Conditional mutation* rule example

```
1 rule VariableExpr2IntVal {
2   from
3     s : CPPivot!VariableExpr(
4       s.declaration.oclIsTypeOf(CPPivot!EnumLiteral)
5     )
6   to
7     t : CPPivot!IntVal(
8       value <- s.declaration.getEnumPos
9     )
10 }
```

3.3 Implementing Transformation Analysis

Transformation analysis is a case of Higher-Order Transformation [19] (HOT): it is a transformation that takes as input another transformation to be analyzed, and produces as output a model containing the analysis result. This HOT uses OCL expressions over the ATL metamodel, which is the metamodel of the language in which the transformations to analyze are written. These expressions recognize the patterns presented in Section 3.2. Then, an analysis model is created that relates concepts of the pivot metamodel to recognized patterns.

The main objective is to deliver a result that a user may understand and interpret. Consequently, special care was given to the rendering of the results. Figure 3 shows how the whole process is implemented. It starts from a collection of n ATL transformations T_1 to T_n conforming to the ATL metamodel. Transformation t_1 is applied to these transformations in order to obtain model T_{1-n} conforming to the TA (for Transformation Analysis) metamodel. This model contains the raw results of the analysis.

Then, transformation t_2 is applied in order to obtain model T'_{1-n} that conforms to a generic Table metamodel. This model may then be rendered to concrete display surfaces like HTML using transformation t_3 , or \LaTeX using transformation t_4 . The HTML rendering leverages the metamodels and transformation presented in [20], and available from Eclipse.org. The \LaTeX rendering was specifically developed for the work presented in this paper. The tables given as example in Section 4 below have been generated automatically using the process depicted here. All metamodels conform to the KM3 [10] (Kernel MetaMeta-Model) metamodel.

Although other techniques could have been used for the implementation, the whole transformation analysis and rendering process is defined in terms of models, metamodels, and transformations. This is an example of the unification power of models [3].

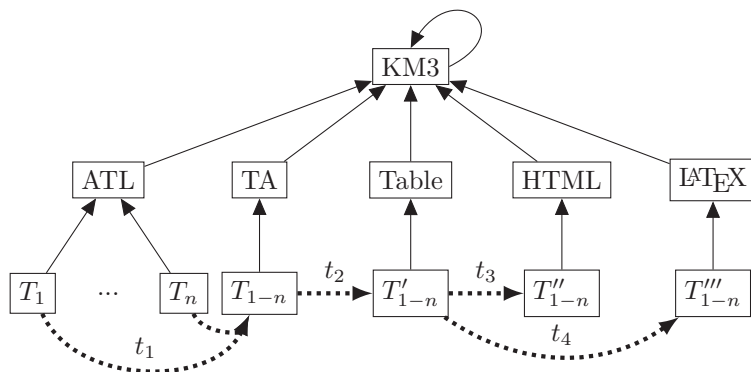


Fig. 3. Transformation analysis and results rendering

4 Experiments

4.1 Application to the Motivating Example

In the motivating example presented in Section 2 (see Figure 2), we consider five endogenous transformations achieving the following reformulation tasks:

- **Class and objects removal.** This complex endogenous transformation is decomposed in two steps. The first step removes classes and does not copy their features. Variables with a class type are mutated in an untyped record definition that is a duplication of the class features. Other variables — with a primitive type like integer, real or boolean — are simply copied like other elements not being contained in a class declaration. The second step flattens record elements to get only variables with a primitive type.
- **Enumeration removal.** Some CP solvers do not accept symbolic domains. Thus, variables with a type being an enumeration are replaced by integer variables with a domain ranging from 1 to the possible number of symbolic values.
- **Useless If removal.** Boolean expressions used as tests in conditional if statements can be constant. In this case, it can be simplified, by removing conditional if elements and keeping only the relevant collection of statements.
- **For loops removal.** This reformulation task is implemented as a fixed point transformation followed by the useless if removal transformation. In the fixed point, each step removes only the deepest loops, i.e. loops that do not contain other loops. To ease the loops removing task, this composite element is replaced by another composite one being a conditional statement with an always true boolean test (i.e., a block).

We have applied on this example the HOT presented in the previous section. The results are detailed in the two following tables, which were automatically generated.

First, Table 2 presents the names of ignored in and out concrete concepts for each analysed transformation. These concepts are defined as concrete in the pivot metamodel, but they do not appear in any OCL expression of transformations. We can see, there is only one in ignored concept considering the record removal step. Indeed, this transformation was written with the assumption of being launched after the class instantiation transformation. Looking at the generated models, several concepts are missing, such as Class and Record for the record removal transformation.

Second, Table 3 gives more details on what endogenous transformations really do. Each line corresponds to an endogenous transformation analysis. Each column details the characteristics — always, conditionally and lazily — of none, one, several, or all other concepts. These characteristics are detailed for copy and mutation rules.

4.2 Interpreting the Results

Typing source and target models. The results given by Table 2 can be used to finely type authorized source and target models of the transformation. The

Table 2. Experimental results: ignored elements

Transformation	Ignored in metamodels	Ignored out metamodels
classInstantiation		Class
enumRemoval		EnumLiteral, Enumeration
forallRemoval		
recordRemoval	Class	Class, Record
uselessIfRemoval		

set of authorized element types can be obtained by computing the difference between the set of all metamodel concepts and those presented in Table 2. It must be noted that looking only at the concepts in source patterns is not enough, since OCL navigation expressions can be used to explore and grab the elements contained in one being removed. Moreover, this information is only an approximation of the actual domain and codomain of the transformations, as described in Section 3.

Inferring partial transformation meaning. Considering Table 3, we can try to interpret the discovered knowledge to infer the transformation meaning. In the case of the class instantiation transformation, we can see that the only concept never copied and never mutated is the class concept. Since it is not in Table 2, it appears within OCL expressions, but it never appears within source patterns. It seems logical, since the aim of this transformation is to remove class statements by expanding their features. Then, variable elements are conditionally copied and conditionally mutated. Indeed, variable types are checked to know if they must be copied (i.e., their type is a primitive type) or if they must be mutated into record elements. Several concepts are always copied and never mutated. They correspond to type definitions or the root model concept, i.e. all concepts that can not be contained in a class. Finally all other concepts are conditionally copied and never mutated. It is checked they do not appear in a class before copying them.

Considering this knowledge, we can deduce that this transformation eliminates class elements, even if they are used within OCL navigation expressions. Variables are copied or mutated, whereas other elements are copied (some of them under a condition). So, this transformation mainly act on two types of elements: class and variable. We may use the set of element types occurring in the target patterns to know the sub-metamodel to which generated models conform.

Looking at the useless if removal transformation, we can easily infer its meaning. Indeed, only the if statements are conditionnally copied, while all other elements are always copied. Then, only some if statements are processed and might be removed.

Discovering fixed point transformations. A transformation having a fixed point semantics may have its codomain equal to its domain. It may focus only on a few concepts to conditionally mutate and to conditionally copy. All other

Copy	lazily, cond.	never	lazily, cond.	cond.	never	always	cond.
Mutation	cond.	never	never	cond.	cond.	never	never
classInstantiation	NONE	Class	NONE	Variable	NONE	EnumLiteral, Predicate, Enumeration, DataType, Model	ALL OTHER
enumRemoval	NONE	EnumLiteral, Enumeration	NONE	Variable, VariableExpr	NONE	ALL OTHER	NONE
forallRemoval	Forall, VariableExpr	NONE	ALL OTHER	IndexVariable	NONE	EnumLiteral, Predicate, Enumeration, Constant, DataType, Variable, Record, Class, Model, Array	SetDomain, IntervalDo- main
recordRemoval	NONE	Record	NONE	NONE	PropertyExpr	EnumLiteral, Predicate, In- dexVariable, Constraint, Enumeration, Constant, DataType, If, Model, Forall	ALL OTHER
uselessIfRemoval	NONE	NONE	NONE	NONE	NONE	ALL OTHER	If

Table 3. Experimental results: referenced elements

concepts may be only copied. This pattern may allow us to detect whether an endogenous transformation could be applied in a fixed point scheme. In Tables 2 and 3 we see that the forall removal transformation matches this pattern. Looking only at Table 3, we may think that the enumeration removal transformation is also a fixed point transformation processing variables. However, Table 2 shows that its main goal is to remove enumerations, because its domain and its codomain are not equal (i.e., it removes all enumerations in one step).

5 Discussions

5.1 Application to Exogenous Transformations

The approach presented in this paper could be extended to support exogenous transformations. Thus, looking at the source patterns and all OCL expressions, we can define the refined type of source models of a transformation (i.e., a more precise definition of its domain). To get the refined type of target models (i.e., a more precise definition of the codomain), we just have to collect the set of concepts occurring in target patterns.

Moreover, we can consider most endogenous transformations as exogenous transformations between two sub-metamodels of the same metamodel. Then, the chaining of endogenous transformations can be transformed into a problem of chaining exogenous transformations. Inferring the meaning of an endogenous transformation may not be necessary (in most cases), since its main task may be to remove or add elements of a given type. However, more complex endogenous transformations may be more difficult to finely chained, since their meaning is necessary to understand how to use them. The knowledge collected in Table 3 is an attempt at achieving this goal with high-level characteristics on concepts. However, this knowledge does not focus on how matchings are performed in rules. Using a more detailed analysis, we could generate weaving models relating to model transformations and then analyze them. However, these models would be more verbose than Table 3. We could also try to analyse OCL expressions and mappings in transformation rules. Although, the cost and the difficulty of our approach is almost negligible when compared to these deeper analysis.

5.2 Debugging Transformations

The knowledge discovered through our analysis transformation can be used in debugging model transformations (exogenous or endogenous). Indeed, when a metamodel contains many concepts, a software engineer may forget to define all the corresponding rules. Thus the results from Table 2 can be directly used, but also the column of Table 3 that corresponds to elements never copied and never mutated. Other columns may also be useful to check that concepts are well classified and no copy or mutation rule are missing.

The data in Table 3 can also be used to discover mistakes in naming meta-model concepts in some rules or helpers. Indeed, some concepts of a metamodel

may rarely have instances in models, and rules dealing with them may not be called. Thus, no error occurs even if the transformation contains some careless mistakes. In the case of our motivating example, we discovered several ill-written rules and helpers dealing with specific CP concepts that do not occur in our CP models.

6 Conclusion

In this paper, we addressed the problem of chaining model transformations. This problem is illustrated on a pivot metamodel for Constraint Programming (CP) that is used for translations between CP languages. Several issues are tackled in order to safely chain transformations. Thus, a higher-order transformation is proposed to statically analyze model transformations. It focuses on source and target concepts, thus defining refined metamodels to which models conform (i.e., more precise definitions of domains and codomains of model transformations). It also extracts some knowledge on how source concepts are processed and assigns characteristics to each concept: always copied, conditionally copied, lazily copied, never copied, always mutated, etc. Considering these characteristics, we are able to find element types that are mainly processed. This process is not accurate enough to exactly infer the meaning of model transformations (it is an abstraction), but it allows us to assert some constraints on how to chain several endogenous transformations. The contributions of this paper are of a different nature and complementary to the results presented in [21]. That paper focuses on a type system for transformation chains, and considers that declared types are good enough, whereas in this paper we have investigated the problem of imprecise transformation typing.

A possible extension of the work presented in this paper would be to go beyond the discovery of hidden chaining constraints and to fully automatize transformation chaining. This automation process could be performed using Artificial Intelligence techniques. An optimization problem can be defined to transform models from a source metamodel to another. The problem naturally comes to find a path in a graph corresponding to a model of the transformations and their types. Some heuristics can be defined to choose the best paths, which may contain as few redundant and as few useless steps as possible.

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